Cumulus Geometry from Satellite and Surface Data at the ARM TWP Site

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Introduction

The multi-angle imaging spectrometer (MISR), a sensor on board the earth observing system (EOS) Terra satellite platform, observes reflected radiation in nine directions with high resolution (~0.275 km). The overall mission of the MISR is to provide continuous, global multi-angle measurements of the reflected radiation from the earth's atmosphere and surface, and thereby create a valuable resource for studying their physical properties (Diner et al. 1999). For *single-layer* marine cumulus clouds, we have demonstrated that satellite-derived basic statistics (mean, variance) of vertical cloud size match closely the corresponding ground-truth values obtained from active remote sensors at the Atmospheric Radiation Measurement (ARM) Tropical Western Pacific (TWP) site at Nauru island (Kassianov et al. 2002, 2003). However, *multi-layered* clouds (e.g., low cumulus and high cirrus) exist frequently in the Tropics (Wang et al. 2000). Therefore, there is a need to evaluate the performance of the cumulus geometry retrieval over multi-layered clouds by using independent ground-based measurements. In this paper, we show the results of this evaluation for a *two-layer* cloud field (low cumulus and high cirrus) observed over the ARM TWP site.

MISR-Data Cloud Retrieval

Data available form MISR overpasses from March 2000 to January 2002 were examined to determine appropriate overpasses for *two-layer* cloud fields (a well-defined single layer of low cumulus clouds with high cirrus clouds) over Nauru and the surrounding area. Here, we present results for one of these appropriate overpasses. For this overpass (July 4, 2001), data from the Af camera are not available, so we use observations from only eight cameras. Figures 1 and 2 show eight MISR images in the 110 x 110 km and 30 x 30 km regions, respectively. From Figure 1, one can see that (1) high cirrus clouds are located over low cumulus clouds quite frequently and (2) the effect of cirrus contamination is a function of the MISR viewing angle. As a result, for a given large scene (110 x 110 km), it is impossible to select a sub-scene (30x30 km) that is not affected by cirrus contamination for all eight cameras. For example, Figure 2 presents a scene where the An camera (nadir direction) shows only low cumulus clouds, but the Da camera (oblique viewing angle ~70 degree) shows both cumulus and cirrus clouds (Figure 2).

Low clouds in comparison with the ocean surface are comparatively bright (e.g., Figure 2, An camera). Therefore, the contrast between cumulus clouds and the ocean is relatively high. For a given MISR image (sub-scene), cirrus contamination can reduce significantly the contrast between cumulus clouds

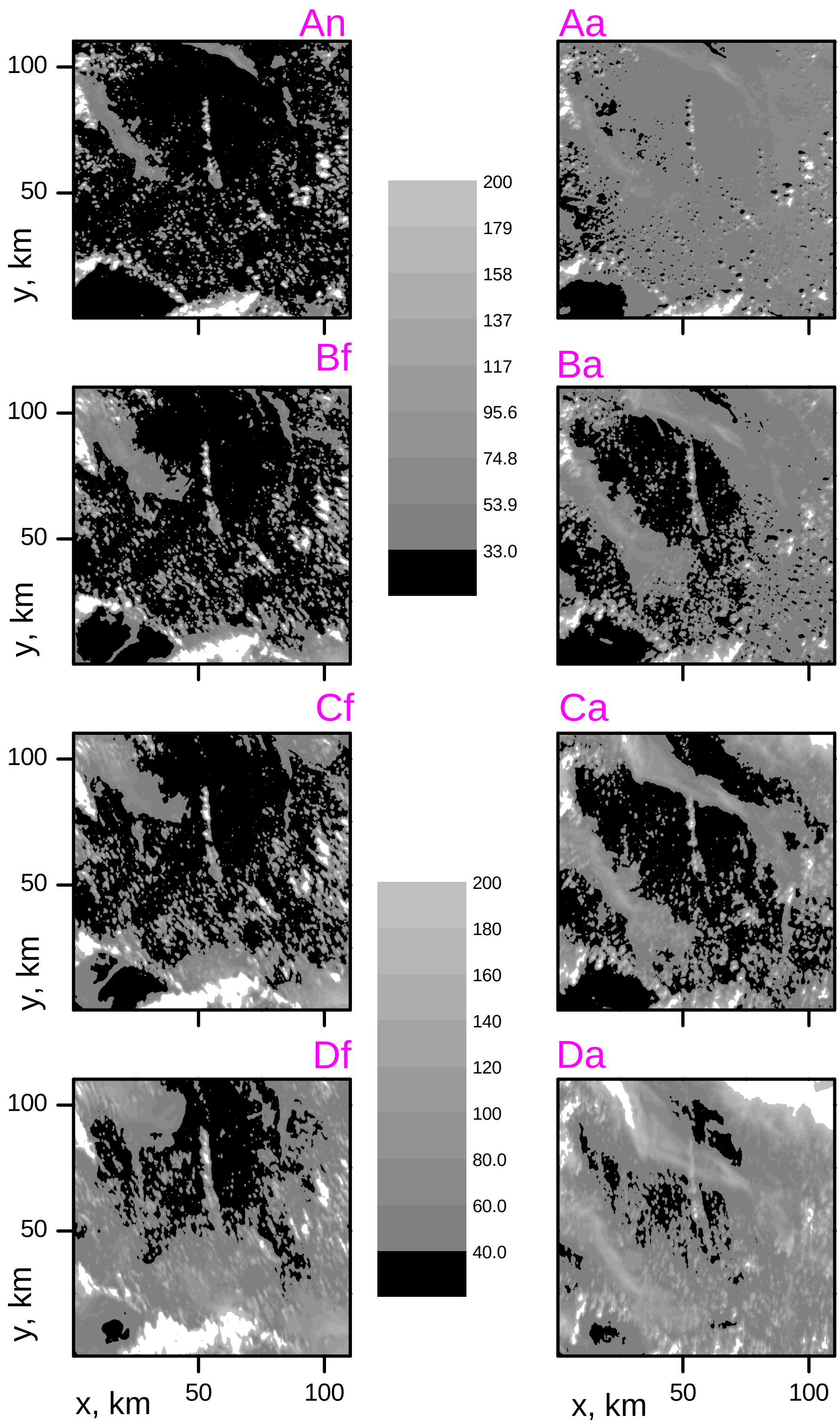

Figure 1. MISR images (110 x 110 km) of cumulus clouds near the ARM TWP site (Nauru) July 4, 2001. These images represent eight cameras with look angles spread out along the MISR flight path in the forward (Bf, Cf, Df), aft (Aa, Ba, Ca, Da) and nadir (An) directions.

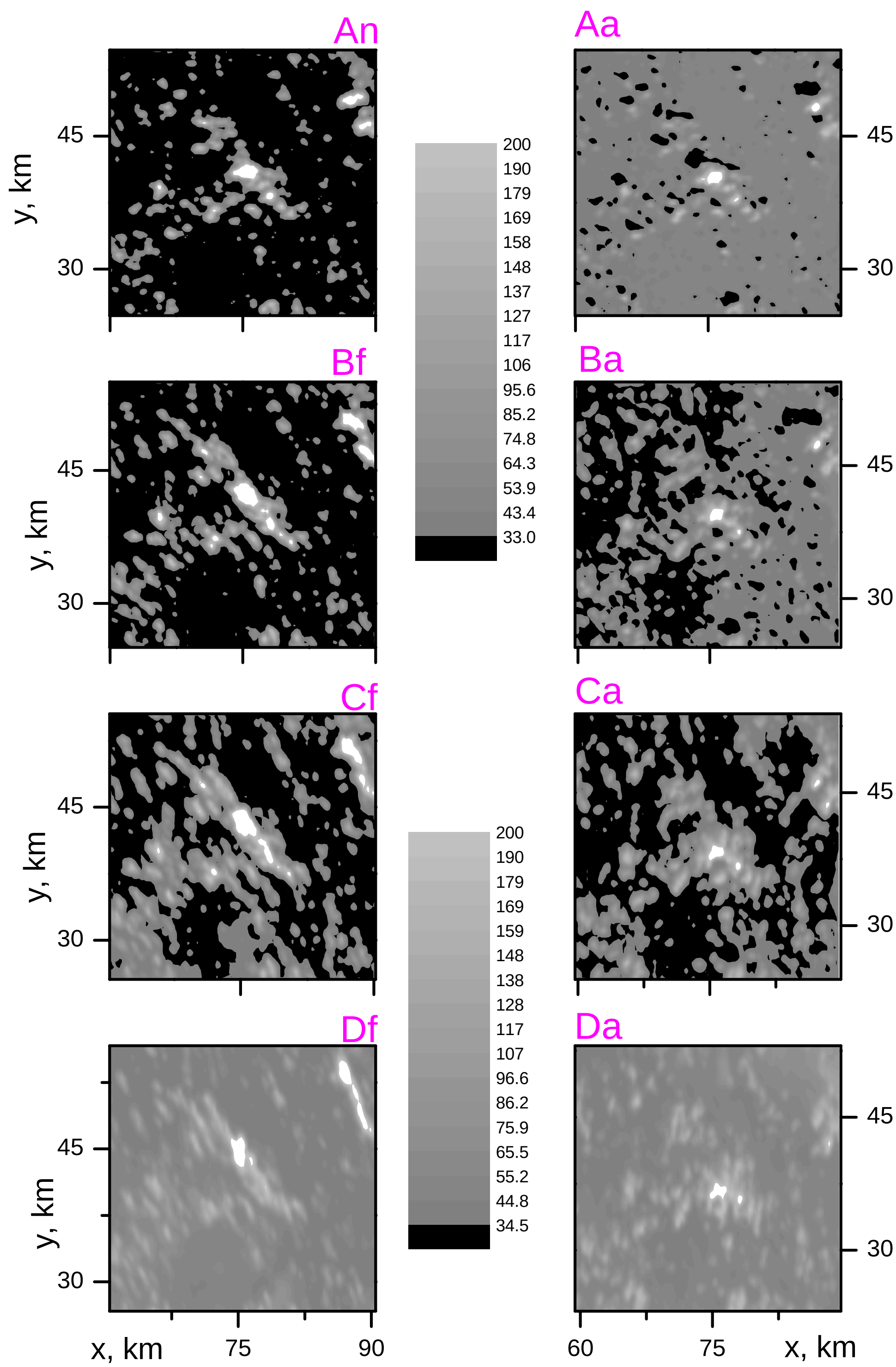

Figure 2. Same as Figure 1 but for smaller (30 x 30 km) regions.

and surrounding areas (e.g., Figures 2, Da camera). Previously (Kassianov et al. 2002, 2003), we demonstrated that the multi-angular cumulus retrieval can be successfully performed for MISR images with relatively high contrast. These images contain cumulus clouds over a dark surface of the ocean. To apply this retrieval for a given two-layer cloud field, we need to select MISR images with a relatively high contrast. This selection allows one to avoid the effects of cirrus contamination and sun glint. To describe quantitatively the contrast for a given MISR image (sub-scene), one can use the variation coefficient (ratio of the standard deviation to the mean value) of the reflected radiance. It follows from Table 1 that the effect of cirrus contamination (e.g., Da camera) can be comparable to the sun glint effect (Aa camera).

For cumulus geometry retrieval, we have to set an appropriate value of the variation coefficient (the variation coefficient threshold). The variation coefficient threshold provides a means for selecting MISR images contaminated strongly by cirrus clouds or affected by sun glint (these images with low contrast are excluded from the cumulus geometry retrieval). Presently, no reliable ways are available to set the variation coefficient threshold unambiguously. Therefore, we performed retrieval for different values of the variation coefficient threshold and then compared the satellite retrievals with ground-based (truth) ones. If the variation coefficient threshold is set to 0.65, we obtained good agreement between satellite-retrieved results and ground truth values. Below, we show only these satellite-retrieved results. Note, three images (three viewing directions), which correspond to the nadir (An camera) and oblique (Bf and Cf cameras) directions, fit the threshold requirement (the variation coefficient is more than 0.65) (Table 1).

Table 1. Basic statistics (Mean, Standard deviation, and Variation coefficient) of reflected radiance, which correspond to the eight MISR images (shown in Figure 2).

Camera	An	Aa	Ba	Bf	Ca	Cf	Da	Df
Mean	30.99	54.33	42.97	37.73	45.65	49.36	66.02	62.23
Stand. dev.	30.89	21.57	24.94	38.52	29.16	39.27	30.41	34.44
Var. coeff.	1.00	0.40	0.58	1.02	0.64	0.80	0.46	0.56

Similar to Kassianov et al. (2002), we performed the cumulus retrieval for two cases. The first case assumes that cumulus cloud base is fixed. The second case assumes that cumulus cloud base is variable. Results of these two retrievals are presented in Figure 3. As can be seen in Figure 3, the satellite-derived mean vertical size of cumulus clouds is almost independent of cloud base variability. However, the standard deviation and probability distribution function (PDF) of cloud vertical size are sensitive to the cloud base fluctuations.

Surface-Data Cloud Retrieval

To evaluate the satellite retrieval of cumulus geometry for two-layer cloud fields, we apply independent and combined ground-based radar and lidar observations at the ARM TWP site. This combination provides the best available estimate of cloud boundaries (Clothiaux et al. 2000). The temporal resolution is 10 sec for these ground-based data. The vertical resolution is set to 0.045 km. We use a 1.5-hour temporal sample for our analysis. Since high cirrus clouds are not the subject of this study, we consider only the properties of cumulus clouds. Figure 4 shows a large variability in the cumulus boundaries. For example, the cloud base fluctuations vary over a large range (~0.8 km).

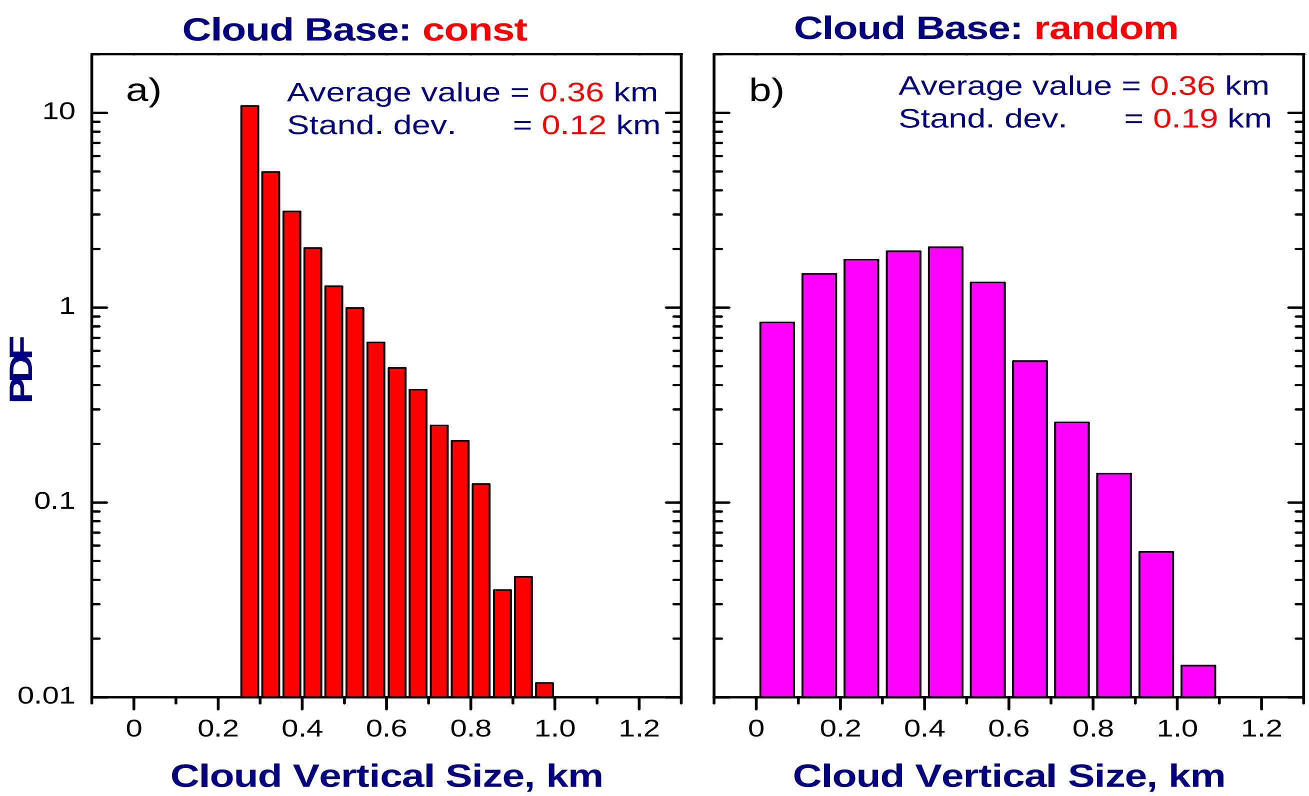

Figure 3. MISR retrievals at the ARM TWP site (Nauru), July 4, 2001: PDF of cloud vertical size for constant (a) and random (b) cloud base.

Similar to Kassianov et al. (2002), we obtain the ground-based statistics for two cases. The first case corresponds to a 10-sec temporal resolution. The second case represents a 90-sec temporal resolution. For a given cloud-level wind speed (the average value ~0.01 km/sec), the 90-sec temporal resolution corresponds roughly to the MISR spatial resolution (the MISR footprint contains roughly 3 x 3 pixels with 0.1-km horizontal size). Figure 5 and Table 2 show the ground-based statistics for these two cases. One can see that the degrading of the temporal resolution does not change the average value of vertical size of cumulus clouds, but reduces slightly its standard deviation (Figure 5 and Table 2).

Comparison Satellite-Retrieved with Ground-Truth Cloud Properties

The mean MISR-retrieved (cloud base is random) and ground-based (90-sec temporal resolution) retrieved values are almost the same (Figures 4b and 5b). While there are small differences between the corresponding standard deviations, we conclude that the basic satellite-derived statistics (mean and

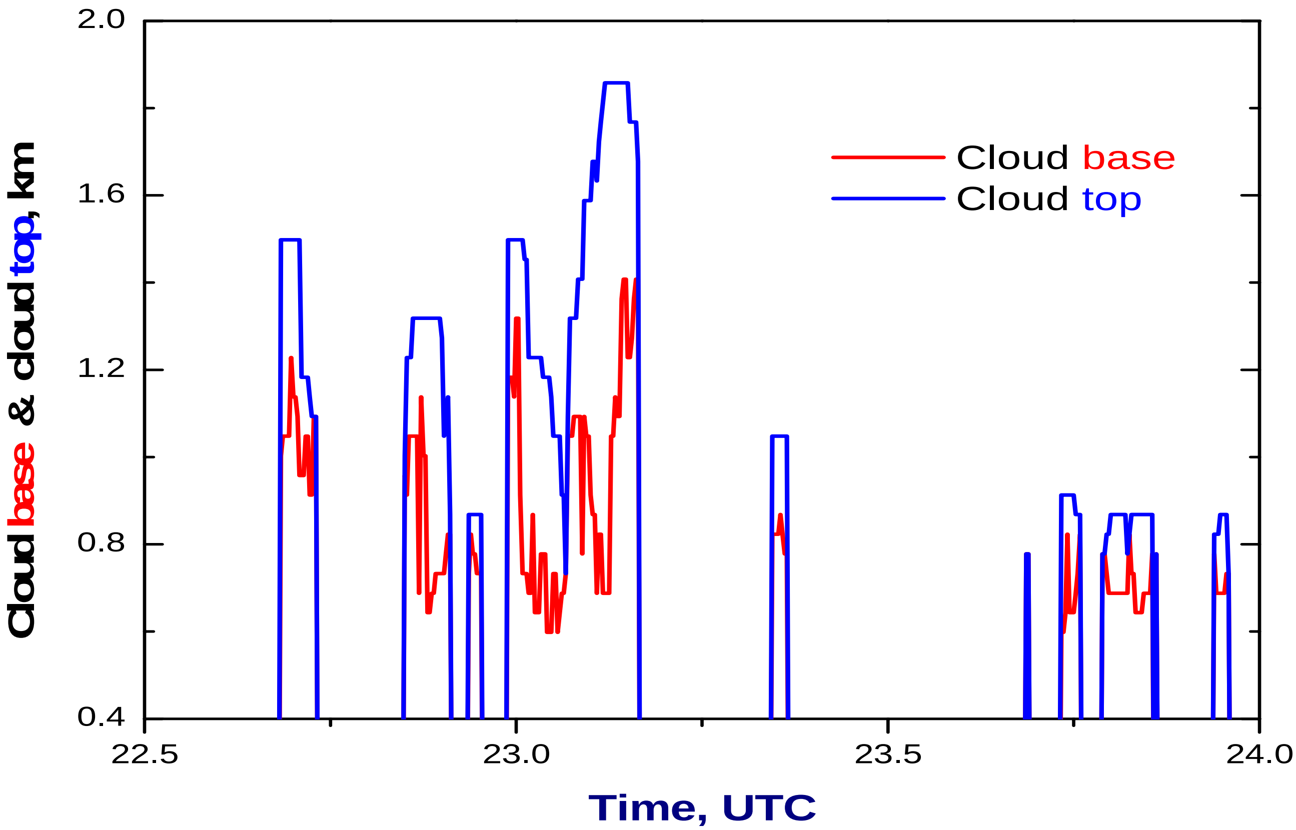

Figure 4. Cumulus clouds from ground-based active remote sensors at the ARM TWP site (Nauru), July 4, 2001: time-height cross sections of cloud base (red) and cloud top (blue).

standard deviation) are similar to those from ground-based data when (1) an appropriate temporal resolution is considered and (2) the cloud base fluctuations are incorporated into the cumulus geometry retrieval. This is in harmony with our previous results found for single-layer cumulus clouds (e.g., Kassianov et al. 2002). Recall, we obtain these good agreements for a selected area (~30 x 30 km) of a *two-layer* cloud field (low cumulus and high cirrus). This area, observed in nadir (An camera) and two oblique (Bf, Cf cameras) directions, contains mainly cumulus clouds over a dark surface of the ocean. The MISR images, that are corresponding to these three cameras (viewing directions), have relatively high contrast. For other viewing directions, MISR images were contaminated strongly by cirrus clouds or affected by sun glint, therefore, these images (with low contrast) are excluded from the cumulus geometry retrieval.

Summary

At the ARM TWP site (Nauru), low cumulus and high cirrus occur frequently. For a two-layer cloud field (low cumulus and optically thin high cirrus), we evaluate the potential for deriving the basic statistics (mean, standard deviation) of the cumulus vertical size from multi-angle satellite measurements. We use both MISR data and ground-based observations (July 4, 2001) at the ARM TWP site for this evaluation. Cirrus contamination and sun glint can reduce significantly the contrast of MISR

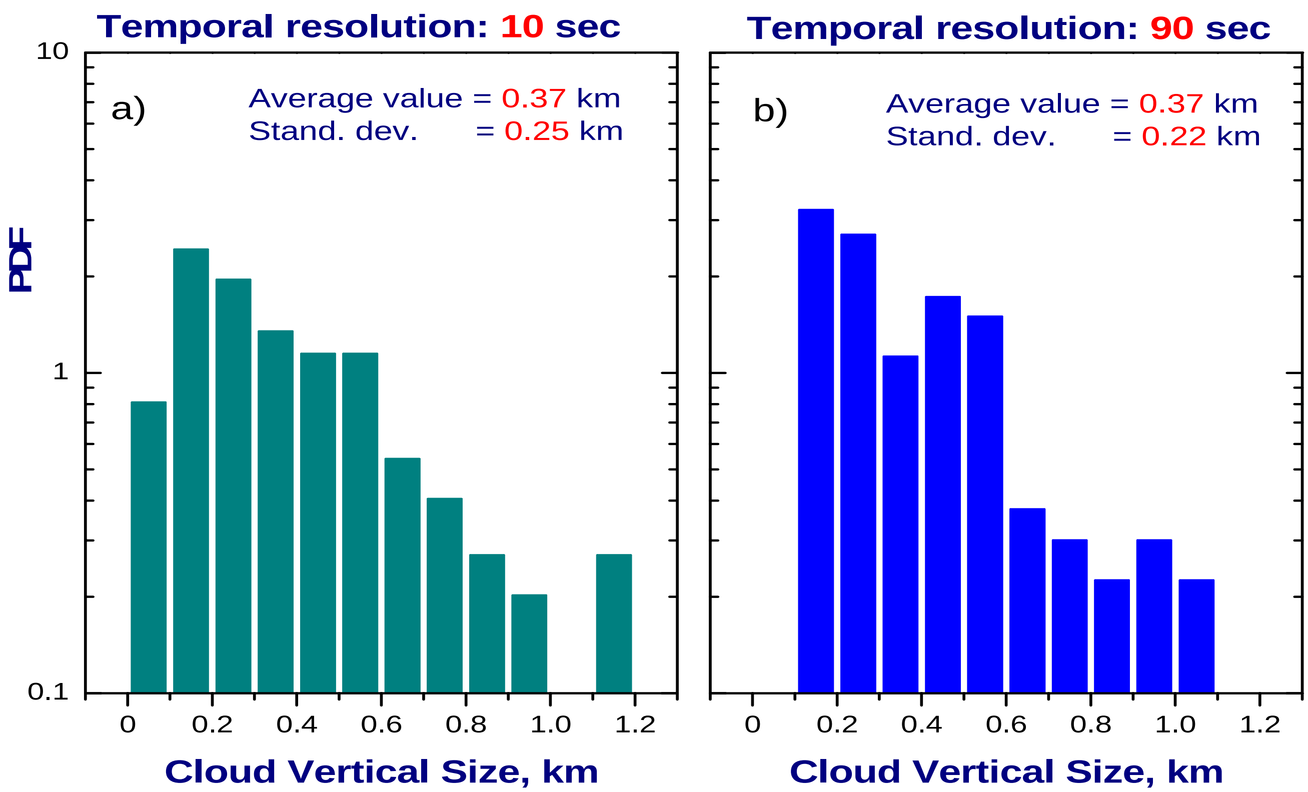

Figure 5. Ground-based retrievals at the ARM TWP site (Nauru), July 4, 2001: PDF of cloud vertical size for different temporal resolutions.

Table 2a. Statistics of cloud top, cloud bottom, and cloud vertical size (thickness) for the ground-based dataset from 22.5 to 24 UTC, July 4, 2001. Temporal resolution is 10 sec.

	Mean, km	Standard Deviation, km	Minimal, km	Maximal, km
Cloud Top	**1.23**	**0.33**	**0.78**	**1.86**
Cloud Bottom	**0.86**	**0.21**	**0.60**	**1.41**
Cloud thickness	**0.37**	**0.25**	**0.05**	**1.17**

Table 2b. Same as Table 2a but temporal resolution is 90 sec.

Cloud Top	**1.23**	**0.30**	**0.85**	**1.86**
Cloud Bottom	**0.86**	**0.17**	**0.65**	**1.34**
Cloud thickness	**0.37**	**0.22**	**0.13**	**1.00**

images and, therefore, can strongly affect the multi-angle satellite retrieval of cumulus clouds. To remove the effect of cirrus contamination, we select a sub-scene (~30 x 30 km) which is cirrus-free for nadir (An camera) and two oblique (Bf and Cf cameras) directions. Also, these three viewing directions are not subject to the sun glint effect. As a result, these MISR images (corresponding to An, Bf, and Cf cameras) have relatively high contrast. For these images, we applied the cumulus geometry retrieval as described in Kassianov et al. (2002, 2003). We illustrated that using a limited number of MISR images (or limited number of viewing directions) can be applied to obtain the satellite-derived basic statistics that are similar to those from ground-based measurements.

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References

Clothiaux, E., T. Ackerman, G. Mace, K. Moran, R. Marchand, M. Miller and B. Martner, 2000: Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the ARM CART sites. *J. Appl. Meteorol*., **39**, 645-665.

Diner, D., G. Asner, R. Davies, Y. Knyazikhin, J.-P. Muller, A. Nolin, B. Pinty, C. Schaaf, and J. Stroeve, 1999: New directions in earth observing: Scientific applications of multiangle remote sensing. *Bull. Amer. Meteorol. Soc*., **80**, 2209-2228.

Kassianov, E. I., T. P. Ackerman, and R. T. Marchand, 2002: MISR-Derived Statistics of Cumulus Geometry at TWP Site. In *Proceedings of the Twelfth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, ARM-CONF-2002. U.S. Department of Energy, Washington, D.C. Available URL: http://www.arm.gov/docs/documents/technical/conf_0204/kassianov(2)-ei.pdf

Kassianov, E., T. Ackerman, R. Marchand, and M. Ovtchinnikov, 2003: Satellite multi-angle cumulus geometry retrieval: Case Study. *J. Geophys. Res*., **108**, NO.D3, 4117, doi:10.1029/2002JD002350.

Wang, J., W. Rossow, and Y. Zhang, 2000: Cloud vertical structure and its variations from a 20-yr global rawinsonde dataset. *J. Climate*, **13**, 3041-3056.